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# Record power, ultra-broadband supercontinuum source based on highly GeO<sub>2</sub> doped silica fiber

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**Abstract:** We demonstrate highly germania doped fibers for mid-infrared supercontinuum generation. Experiments ensure a highest output power of 1.44 W for a broadest spectrum from 700 nm to 3200 nm and 6.4 W for 800 nm to 2700 nm from these fibers, while being pumped by a broadband Erbium-Ytterbium doped fiber based master oscillator power amplifier. The effect of repetition frequency of pump source and length of germania-doped fiber has also been investigated. Further, germania doped fiber has been pumped by conventional supercontinuum source based on silica photonic crystal fiber supercontinuum source. At low power, a considerable broadening of 200-300 nm was observed. Further broadening of spectrum was limited due to limited power of pump source. Our investigations reveal the unexploited potential of germania doped fiber for mid-infrared supercontinuum generation. These measurements ensure the potential of germania based photonic crystal fiber or a step-index fiber supercontinuum source for high power ultra-broad band emission being by pumped a 1060 nm or a 1550 nm laser source. To the best of our knowledge, this is the record power, ultra-broadband, and all-fiberized supercontinuum light source based on silica and germania fiber ever demonstrated to the date.

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**OCIS codes:** (320.6629) Supercontinuum generation; (060.4370) Nonlinear optics, fibers; (140.3510) Lasers, fiber; (140.3070) Infrared and far-infrared lasers; (060.2280) Fiber design and fabrication.

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## 1. Introduction

Fiber based supercontinuum (SC) sources are great sources of light as they offer a wide range of wavelengths, good beam quality, high spectral density, and compact size [1,2]. Silica based photonic crystal fibers (PCF) have been used as non-linear medium for spectral broadening successfully thanks to the strong confinement [3]. However, due to high phonon energy of silica glass, the broadening is limited up to 2.4  $\mu\text{m}$ . In 1975 Maurer and Schultz proposed germania glass (GeO<sub>2</sub>) as a base material for low-loss optical fibers at longer wavelength thanks to the shift of intrinsic IR absorption and Ge-OH absorption bands to longer wavelengths [4]. Highly GeO<sub>2</sub> doped fiber has been used as a non-linear fiber, although GeO<sub>2</sub> mol % has been limited to lower than 30% [5]. A fluorine doped cladding has been used in

order to increase the nonlinearity, these fibers are known as highly non-linear fibers (HiNL). Several experiments on SC generation have been carried out using these HiNL fibers [6–9]. Nicholson *et al.* demonstrated an all-fiberized femtosecond SC generation using a UV exposed HiNL fiber, a spectrum spanning from 850 nm to 2700 nm was obtained with an output power of 400 mW. However, exposure to UV radiation was necessary to red-shift the spectrum, unexposed sample remains confined to 975 nm [8]. Xia *et al.* demonstrated a spectrum spanning from 800 nm to 3000 nm with an output power of 27 mW at 5 kHz repetition frequency using nanosecond laser diode pulses [9]. Further scaling the repetition frequency to 1 MHz increased the average power up to 5.3 W, although the spectrum was limited to ~2700 nm [9].

However, it was not until 2004 that low-loss high concentration of GeO<sub>2</sub> doped fibers were fabricated. In a series of experiments, researchers at FORC, Russia fabricated several GeO<sub>2</sub> doped fibers with concentrations varying from 51 mol % to 97 mol % [10–12]. The losses were lower than 120dB/km at 1.9–2  $\mu$ m for all of these fibers. Initially highly efficient Raman fiber lasers emitting around ~2.1  $\mu$ m with record power were demonstrated for the first time using these highly GeO<sub>2</sub> doped (>70 mol %) fibers [13,14]. Later on, these fibers were characterized for SC experiments at different groups. In 2012, Kamynin *et al.* pumped a 64 mol % Ge-doped fiber by a pump source lasing at 1.59  $\mu$ m with pulse width of 35 ns at a repetition frequency of 4.4 kHz [15]. A spectrum ranging from 800 nm to 2700 nm was obtained from a 7 m fiber with a maximum output power of 500 mW. A significant asymmetry could be observed in the spectrum, as most of the power resided in 1500 nm to 2600 nm wavelength region. In 2012, Anashkina *et al.* demonstrated a femtosecond SC generation in the 1.0–2.6  $\mu$ m wavelength range [16]. Optical solitons with duration of 80–160 fs were measured in the 2–2.3  $\mu$ m wavelength range. In 2013, Zhang *et al.* demonstrated a continuum extending from 1.9  $\mu$ m to 3  $\mu$ m, pumped by a thulium-doped MOPA fiber system lasing at 1.95  $\mu$ m with sub picosecond pulses of 12 kW peak power [17]. In this experiment, a 3.4 m long 75 mol % GeO<sub>2</sub> doped fiber was used. In 2014 Dvoyrin *et al.* demonstrated an SC with a 10 dB bandwidth of 1.93  $\mu$ m–3.18  $\mu$ m with up to 3.8 W of output power pumping with an all-fiber MOPA pulsed system with a Tm-doped fiber mode-locked seed laser at a 44 MHz repetition frequency [18]. In this experiment, a pure GeO<sub>2</sub> doped fiber with 9  $\mu$ m core diameter was used and the obtained spectrum suffered from a broad OH absorption peak around 2700 nm. In 2016 Yang *et al.* demonstrated an SC with a 10dB bandwidth of 717 nm to 2998 nm, with a total of 450 mW output power [19]. A pure GeO<sub>2</sub> core fiber of 3  $\mu$ m core diameter was used. Fiber was pumped by a simple source consisting of a seed laser diode delivering a 1.1 ns pulse width at a repetition frequency of 100 kHz with an average power of 5 mW, which was further amplified to 506 mW by an erbium-ytterbium doped fiber amplifier. Authors claimed a zero dispersion wavelength (ZDW) of 1.426  $\mu$ m for a pure GeO<sub>2</sub> fiber, which is significantly shorter than the measured ZDW of 1.73–1.74  $\mu$ m of GeO<sub>2</sub> glasses thanks to the strong waveguide contribution [20,21]. Nonetheless the result obtained by Yang *et al.* is the best performance in terms of bandwidth from a GeO<sub>2</sub> doped fiber.

The above mentioned experiments highlight the importance of the pump wavelength for SC generation in a highly GeO<sub>2</sub> doped fiber. A pump source near 1550 nm has led to spectral broadening towards visible wavelength, on the contrary a pump source near 2000 nm limits broadening towards blue wavelength to 1700 nm [15,17–19]. The measured ZDW of GeO<sub>2</sub> glass is around 1.73–1.74  $\mu$ m, however for a GeO<sub>2</sub> doped fiber, the ZDW will depend on the exact concentration of GeO<sub>2</sub> (as it decides NA of fiber as well) and core diameter. Therefore a broadband pump source emitting in the range of 1400 nm to 2000 nm can be an ideal source for pumping a highly GeO<sub>2</sub> doped fiber.

In this paper, we report SC sources based on a GeO<sub>2</sub> doped core fiber, which is being pumped by a broadband four-stage Er-Yb doped fiber based master oscillator power amplifier (MOPA). We use a high power, in-house constructed four-stage MOPA based on Er-Yb based fiber, which source emits over a broadband range thanks to the in-amplifier spectral

broadening. This versatile broadband source is quite suitable for efficient pumping any Ge-doped fiber having ZDW larger than  $1.4 \mu\text{m}$ . To the best of our knowledge, this is a record power for an ultra-broadband, all-fiberized, and compact device size SC light source based on silica and germania fiber, ever demonstrated to date.

## 2. Pump source and $\text{GeO}_2$ doped fiber

An all-fiberized compact 4-stage MOPA was constructed in-house, a diode laser being directly modulated was used as a seed source. The pulse width was fixed to 1 ns ( $\pm 100$  ps) and frequency could be varied from 10 KHz to 20 MHz. The signal was further amplified in 3 stages. Figure 1(a) shows the pump power of the final stage and the final output power versus pump current. A highest power of 13.17 W was obtained at 34 W of pump power with a nearly 40% slope efficiency at 10 MHz repetition frequency. Figure 1(b) shows the output spectrum for three different pump currents 1 A, 4 A, and 8 A corresponding to 0.53 W, 6.39 W, and 13.17 W output power respectively at 10 MHz repetition frequency. The spectrum extends up to 2400 nm thanks to the in-amplifier spectral broadening.

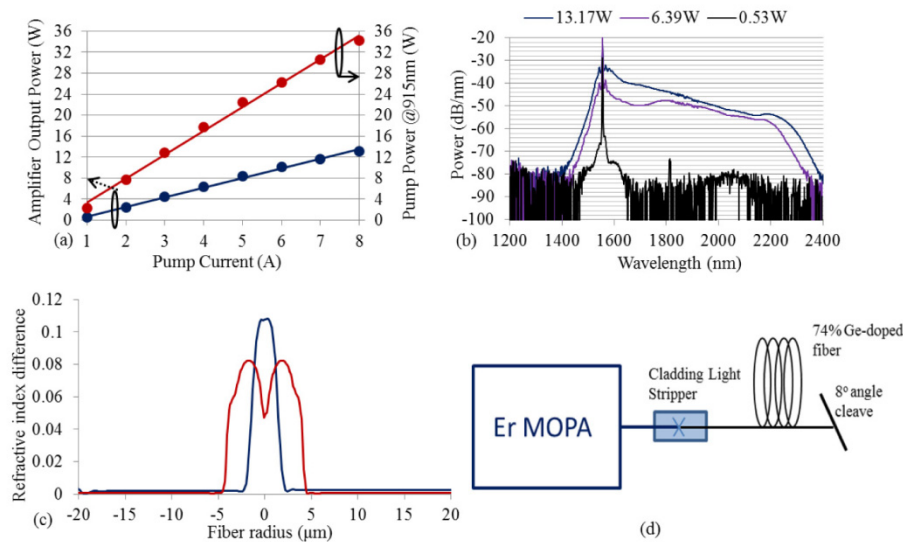


Fig. 1. (a) Output power and pump power with respect to pump current for a 4-stage Er-fiber based MOPA at 10 MHz repetition frequency (b) output spectrum of Er-MOPA at different output power at 10 MHz repetition frequency (c) measured refractive index profile of both fibers (d) schematic of SC experiments.

Two germania doped silica fibers, with  $\text{GeO}_2$  molar concentration of around 74% and 56% were used in this work. The first fiber (74 mol %) has a core diameter and NA of  $3.5 \mu\text{m}$  and 0.58, respectively, with a cladding diameter of  $125 \mu\text{m}$ . The second fiber (56 mol %) has a core diameter and NA of  $9 \mu\text{m}$  and 0.5 respectively, with a cladding diameter of  $150 \mu\text{m}$ . Figure 1(c) shows the refractive index profile of both fibers. These fibers were fabricated in a series of experiments to increase the content of Ge mol % using an optimized modified chemical vapor deposition (MCVD) process at COFT, NTU Singapore by Sidharthan et al. [22]. Considering the fact that tight confinement leads to a higher non-linearity, the whole preform having 74 mol % was drawn to a fiber having  $3.5 \mu\text{m}$  core diameter and  $125 \mu\text{m}$  cladding diameter. Later on we realized that the delivery fiber of the pump source is a standard PM-1550 nm double clad passive fiber, which has a core diameter of  $10 \mu\text{m}$  with an NA of 0.12. The significant difference between core diameter and NA of the delivery fiber and the Ge-doped fiber leads to poor coupling efficiency. Therefore we drew the 56 mol % preform to a core diameter of  $9 \mu\text{m}$  and  $150 \mu\text{m}$  cladding diameter. Figure 1(d) shows the



schematic of the SC source where the pump source is spliced to the Ge-doped fiber, and the output end of the fiber was cleaved to 8 degree to avoid coupling of back reflected light to the core. A cladding light stripper (CLS) was constructed over the splice point in order to remove uncoupled light. However, due to strong mis-match between core diameters of 10  $\mu\text{m}$  core diameter delivery fiber and 3  $\mu\text{m}$  core diameter germania fiber, there would have been significant back reflection of light.

### 3. Supercontinuum generation

#### (a) Experiments with with 74 mol % $\text{GeO}_2$ 3.5 $\mu\text{m}$ core diameter fiber

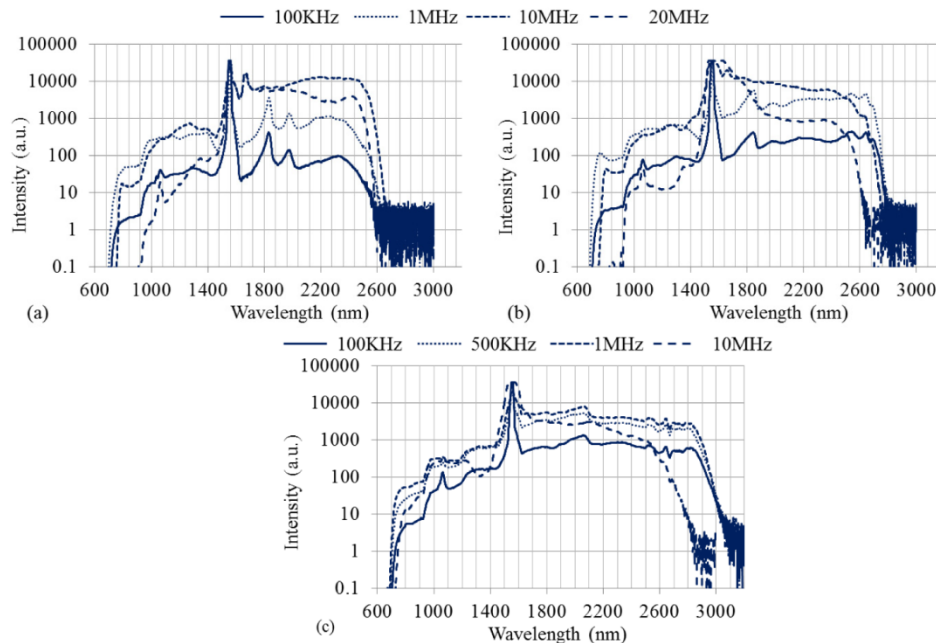


Fig. 2. (a) Output spectrum of SC source at 4 A pump current (corresponding to output power 6.39 W at 10 MHz repetition frequency) for different repetition frequencies and different length of  $\text{GeO}_2$  doped fiber (a) 22 m (b) 5 m (c) 0.9 m long fiber.

Figure 2 shows the output spectrum of the SC source for different fiber lengths and different repetition frequency of the seed source at a constant current of 4 A through the pump diodes. Several fiber lengths of  $\text{GeO}_2$  doped fiber were characterized, although only results for 22 m, 5 m, and 0.9 m are being presented in Fig. 2(a), Fig. 2(b), and Fig. 2(c), respectively. For 22 m long fiber spectral broadening is limited up to 2600 nm. The best result in terms of the most red-shifted spectrum is obtained for 10 MHz repetition frequency, with a trend of increase from 100 KHz to 10 MHz due to the higher average power from the amplifier, but this leads to reduced peak power. At higher repetition frequency the total average power increases, as the MOPA runs more efficiently but when the repetition frequency becomes high the peak power is reduced, which limits the spectral broadening. Therefore at 20 MHz, broadening is weaker than at 10 MHz. Figure 2(b) shows the measured spectra for a 5 m long fiber, which now goes up to 2800 nm. This clearly shows that a broader red shift is obtained with a shorter piece of fiber, revealing the importance of the loss above 2400 nm. For this 5 m long fiber, red-shift of spectrum increases first and with increase in repetition frequency but with further increase it starts decreasing. This shows a clear trade-off between average power and peak power. A comparative analysis of Fig. 2(a) and 2(b) also shows the role of interaction length as well. The optimum frequency (most red-shifted spectrum) is 1 MHz and 10 MHz for 5 m and 22 m long fibers, respectively. For the smaller length of 5 m, a higher

peak power (lower repetition frequency) is required to achieve the most red-shifted spectrum, as the interaction length is short.

The best results in terms of spectral broadening are achieved for a 90 cm long piece of fiber at 1MHz repetition frequency, for which the spectrum goes from 700 nm to 3200 nm. The total output power at 6 A pump current is 1.44 W, the power above 1650 nm is 760 mW, and the power above 2400 nm is 225 mW. To the best of our knowledge, this is the highest power ever reported for such a broad spectrum. Figure 3 shows the measured power for the full spectrum and using long pass filter having cut-offs at 1650 nm and 2400 nm for different lengths (22 m, 5 m, and 0.9 m) and different frequencies. A clear observation is that higher power is obtained for smaller length of fiber. At 1 MHz, the output power of the whole spectrum is 1440 mW, 700 mW, and 240 mW for 22 m, 5 m, and 0.9 m long fibers respectively. Similarly the power measured above 1650 nm and 2400 nm follows the same trend. Again at 1 MHz, the output power above 1650 nm is 760 mW, 280 mW, and 76 mW and the output power above 2400 nm is 225 mW, 85 mW, and 6 mW for 22 m, 5 m, and 0.9m long fibers respectively. We did not run the amplifier at its maximum power, as back reflections due to mis-match in core diameter in the delivery fiber and Ge-fiber could damage the system. In the next sub-section we have used a large core diameter fiber for enhanced coupling efficiency.

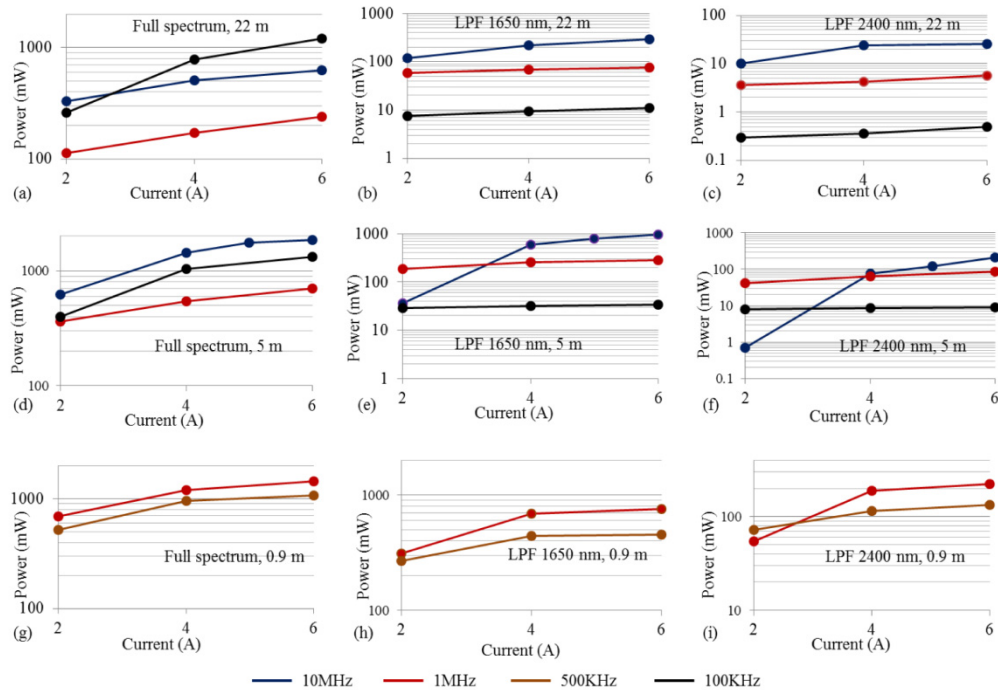


Fig. 3. Output power of the full spectrum, above 1650 nm, and 2400 nm SC source for different pump currents and different repetition frequencies, and different lengths of GeO<sub>2</sub> doped fiber.

In order to further broaden the spectrum, we did some more cut-back measurements. Figure 4 shows the measured spectra for fiber lengths of 80 cm, 70 cm, and 60 cm at 500 KHz and a pump current of 4 A. Clearly the spectrum dies out at 3100 nm and no considerable changes in the red edge of the spectra were observed for the three different lengths.

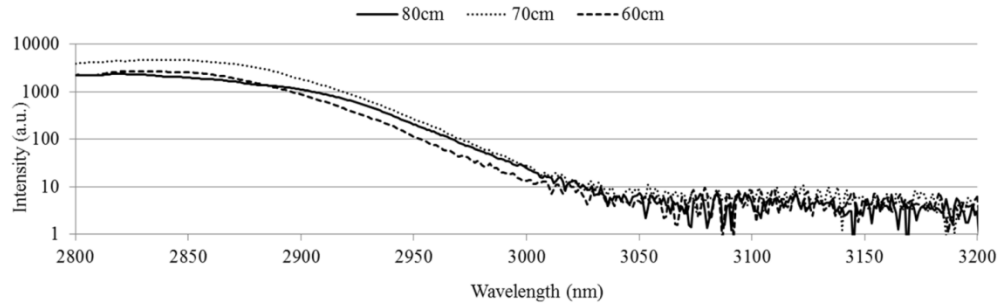


Fig. 4. Different spectra of SC source at 4 A pump current (corresponding to output power 6.39 W at 10 MHz repetition frequency) for different lengths of GeO<sub>2</sub> doped fiber.

The main mechanism of spectral broadening towards longer wavelength here can be understood in terms of soliton self-frequency shift in anomalous region [2]. On the contrary, the spectral broadening towards shorter wavelength can be attributed to formation of non-solitonic dispersive waves [2]. The similar approach has been used for SC broadening for ZBLAN fibers, where the output of Er-amplifier has been used as a pump source in anomalous dispersion region [23].

*(b) Experiments with 56 mol % GeO<sub>2</sub> doped 9  $\mu$ m core diameter fiber*

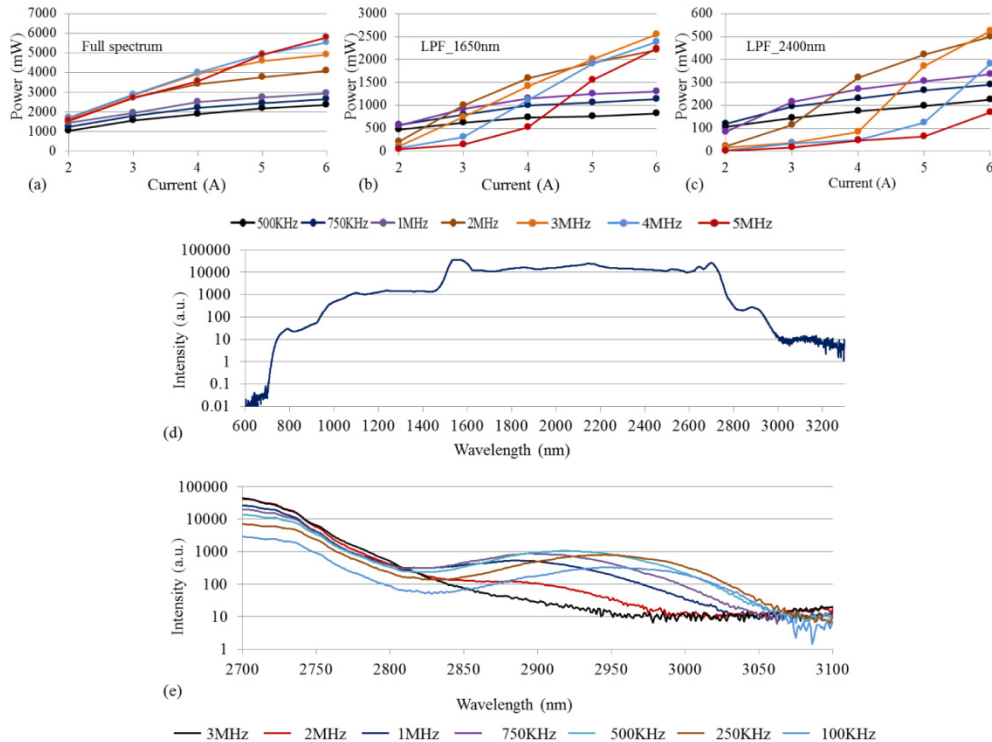


Fig. 5. (a), (b), and (c) show the measured power of full spectrum, above 1650 nm, and above 2400 nm, respectively, for different pump currents and repetition frequencies (d) full spectrum at 6 A and 1 MHz (e) measured spectra for different repetition frequencies at 6 A pump current. The length of fiber is 1.2 m.

In order to further scale the power, we used a second fiber having 9  $\mu$ m core diameter and 150  $\mu$ m outer diameter. The GeO<sub>2</sub> content was found to be 56 mol % from the refractive index



profile. Figure 5 shows the measured output power for different pump currents (2 A, 3 A, 4 A, and 6 A) and different repetition frequencies (500 KHz, 750 KHz, 1 MHz, 2 MHz, 3 MHz, 4 MHz, and 5 MHz) for a 1.2 m long fiber. It is important to analyze these spectra to understand the role of repetition frequency. With increasing frequency, the power of the whole spectrum increases, as the average power of the 1550 nm pump source increases as shown in Fig. 5(a). However, the same trend is not observed for the power measured above 1650 nm and 2400 nm. A trade-off between average power and peak power rules these spectra as observed for the 3.5  $\mu\text{m}$  core fiber. As the main asset of Ge-doped fiber is to push power towards longer wavelength, we consider the optimum frequency at which there is maximum power beyond 1650 and 2400 nm. At 6 A, 3 MHz repetition frequency produces the highest power beyond 1650 and 2400 nm, measured to be, 2.26 W, and 0.53 W, respectively, out of a total power of 4.9 W. It is interesting to note that for whole spectrum the power is highest for 5 MHz, however the power above 2400 nm is the lowest. This is a clear indication of the presence of a trade-off between average power and peak power. It is very important to understand the role of optimum repetition frequency as it can significantly influence the power in the wavelength region of interest. For example, the power above 2400 nm is 170 mW, 525 mW, and 335 mW at 5 MHz, 3 MHz, and 1 MHz, respectively. Therefore a fine tuning of operating repetition frequency is critical. Figure 5(d) shows the measured full spectrum at 4 A pump current and 1 MHz. The spectrum spans from 600 nm to 3200 nm, although most power is limited to the 800 nm to 2700 nm region only. Figure 5(e) shows the measured spectra for repetition frequencies. Clearly there is no significant different between these spectra. Most of the power remains confined to below 2750 nm, which reveals the presence of fiber loss above 2700 nm. It is indeed discouraging to observe that the broadening observed here is less than obtained in the 74 mol %  $\text{GeO}_2$  fiber in the previous sub-section. There can be the following reasons for weaker broadening: reduced non-linearity due to the larger core diameter and higher loss above 2700 nm due to lower  $\text{GeO}_2$  concentration. It might be worth noting the drop in power around 2800 nm which can be associated to OH ions incurred during fiber fabrication. The OH ions normally have fundamental vibration absorption around 2.73  $\mu\text{m}$  and 2.82  $\mu\text{m}$  in case of silica glass and germania glass respectively [24]. In order to further enhance the broadening, we did further cut back and Fig. 6 shows measured spectra for three different lengths of fiber: 120 cm, 60 cm, and 25 cm. It is evident that with reduction in length of fiber, the absorption around 2800 nm appears to disappear.

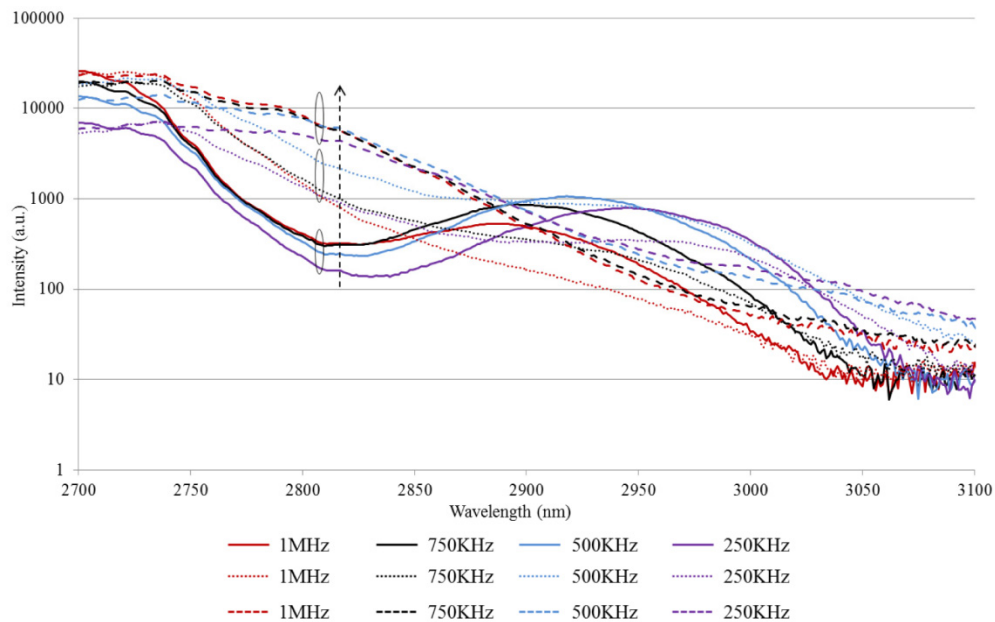


Fig. 6. measured spectra for different length of fibers (120 cm, 60 cm, and 25 cm) at different repetition frequencies. Straight: 120cm, Dot: 60 cm, Dash: 25cm.

Figure 7 shows the measured power for a 60 cm long fiber for different pump currents and different repetition frequencies. Again a trade-off between average power and peak power can be observed similar to Fig. 5(a). Again the optimum frequency is 3 MHz. At 3 MHz, the total power is 5.6 W, the power above 1650 nm is 2.7 W, and the power above 2400 nm is 0.48 W. The overall highest power is 6.4 W for 5 MHz repetition frequency. An interesting conclusion that can be drawn from Fig. 7 is the role of interaction length. This 60 cm fiber provides more power than 120 cm fiber for both the whole spectrum and above 1650 nm, but lower power beyond 2400 nm. A trade-off between interaction length and loss of fiber can explain these observations. With reduction in the length overall power increases due to overall low loss, but the shorter interaction length also leads to lower transfer of power towards longer wavelength.

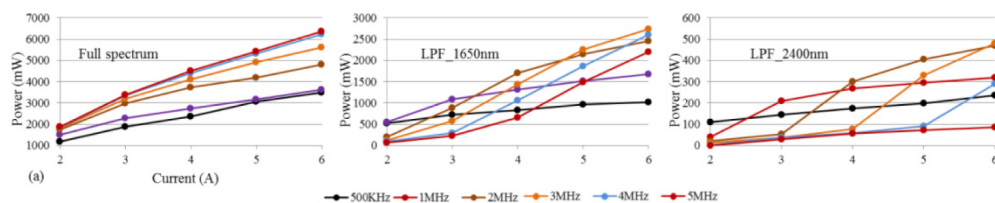


Fig. 7. measured power of full spectrum (a), power above 1650 nm (b), and power above 2400 nm (c) at different currents and different repetition frequencies. The length of fiber is 60 cm.

Therefore, a proper choice of fiber length and optimum repetition frequency is mandatory to obtain a high power and broad spectrum along with power in wavelength region of interest.

#### 4. Pumping with a silica-PCF based SC source

Further in order to judge the potential of a germania doped PCFs for extending the bandwidth of existing source, a commercially available silica PCF based SC source was used to pump a 4 m long 74 mol % Ge fiber. The repetition frequency was fixed to 80 MHz.

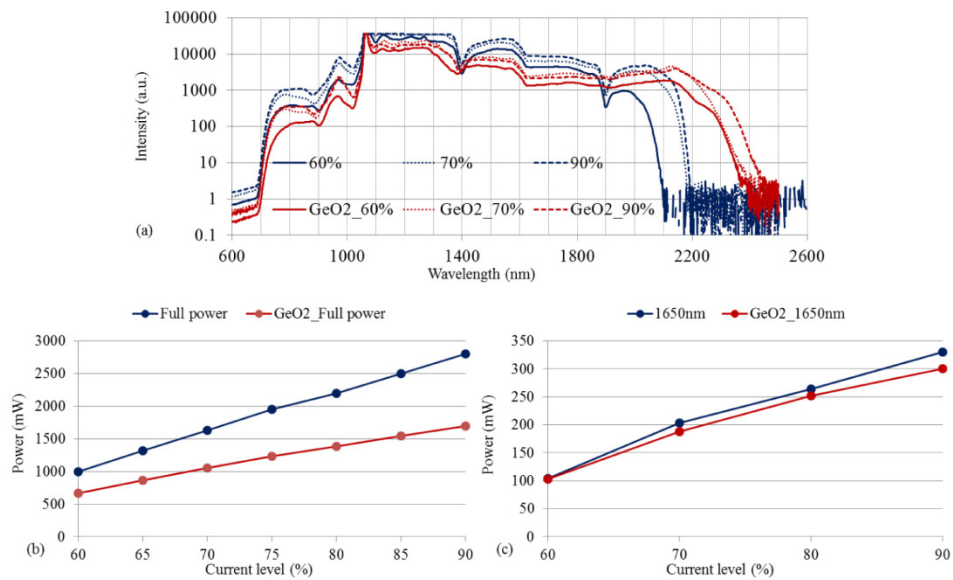


Fig. 8. (a) Output spectrum of SC source and GeO<sub>2</sub>-SC at different seed current (b) Output power of full spectrum and (c) above 1650 nm for both SC source and GeO<sub>2</sub>-SC source.

Figure 8(a) shows the output spectrum of both the silica PCF based SC source (SuperK Power, NKT Photonics) and the GeO<sub>2</sub>-fiber pumped by the SC source for different current levels of the pump source of the SC source. Clearly extension of the red edge can be noticed. A gain of 200 nm to 300 nm spectral width was observed. The output of the SC source was directly butt coupled to the germania fiber, a coupling efficiency of 60% was observed as shown in Fig. 8(b). However, the power level above 1650 nm remains almost the same, as shown in Fig. 8(c). This ensures the transfer of power from 1060 nm towards longer wavelengths. However, due to limited power, extension of the bandwidth remains limited to 2500 nm, which can of course be further extended by increasing peak power or changing the pulse width. We also tried the 56 mol % GeO<sub>2</sub> fiber in this configuration, but did not observe any spectral broadening for the 56 mol % fiber. We believe the lower non-linearity of this fiber and large core diameter leading to a mis-match of soliton order can be a potential cause of this observation [25]. Detailed investigations for this configuration are intended as a future work.

## 5. Discussion and conclusion

We have successfully obtained a wide spectrum from 700 nm to 3200 nm, with a total power of 1.44 W, 760 mW above 1650 nm, and 225 mW above 2400nm from a 3.5  $\mu\text{m}$  core diameter 74 mol % GeO<sub>2</sub> doped fiber. Further, wide spectra from 800 nm to 2700 nm with over all power around 6.4 W has been obtained using a 9  $\mu\text{m}$  core diameter with a lower GeO<sub>2</sub> concentration of 56 mol %. A highest power above 2400nm of 0.53 W was obtained for an overall power of 4.9 W for this 56 mol % GeO<sub>2</sub> doped fiber. To the best of our knowledge, these are the highest power levels reported for such broad spectra in all-fiberized configuration using silica/germania as non-linear fibers. A critical role of fiber length and repetition frequency has been observed in pushing power towards longer wavelength. It is important to note that the OH absorption peak that limits broadening beyond 2700 nm in the large core diameter fiber (9  $\mu\text{m}$ ) can be avoided and has been avoided in the small core diameter fiber (3.5  $\mu\text{m}$ ). A critical analysis of fiber fabrication logs would be required to dig out the reason of substantial OH loss in large core diameter fiber. Unfortunately, the full potential of high power of MOPA with a GeO<sub>2</sub> doped fiber remains unexploited due to strong

mismatch between core diameter of delivery fibers and 3.5  $\mu\text{m}$  core diameter germania doped fiber. This can be an ideal source for meeting the demands of light sources in the 2-3  $\mu\text{m}$  region such as pumping a ZBLAN or InF fiber for further extending the spectrum into the 4 to 5  $\mu\text{m}$  range. Future work can also concentrate on developing highly Ge-doped PCF being able to be pumped by 1060 nm laser source. Previously low concentration Ge-doped PCF has been demonstrated for power scaling in the visible region [26–29]. The present work can make HiNL fibers (Ge concentration lower than 30%) obsolete. These fibers are limited in spectral broadening at both ends (visible and infrared). As mentioned in the introduction, HiNL requires a UV processing to push the blue edge towards visible wavelengths [7,8]. Our investigations prove the immense potential of germania doped fiber for SC generation applications.

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